

Minimal Higgs inflation

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In this paper we propose two simple minimal Higgs inflation scenarios through a simple modification of the Higgs potential, as opposed to the usual non-minimal Higgs-gravity coupling prescription. The modification is done in such a way that it creates a flat plateau for a huge range of field values at the inflationary energy scale $\mu \simeq (\lambda)^{1/4} \alpha$. Assuming the perturbative Higgs quartic coupling, $\lambda \simeq \mathcal{O}(1)$, for both the models inflation energy scale turned out to be $\mu \simeq (10^{14}, 10^{15})$ GeV, and prediction of all the cosmologically relevant quantities, (n_s, r, dn_s^k) , fit extremely well with observations made by PLANCK. Considering observed central value of the scalar spectral index, $n_s = 0.968$, our two models predict efolding number, $N = (52, 47)$. Within a wide range of viable parameter space, we found that the prediction of tensor to scalar ratio $r (\leq 10^{-5})$ is far below the current experimental sensitivity to be observed in the near future. The prediction for the running of scalar spectral index, dn_s^k , approximately remains the same as was predicted by the usual chaotic and quartic inflation scenario. We also computed the background field dependent unitarity scale $\Lambda(h)$, which turned out to be much larger than the aforementioned inflationary energy.

Higgs inflation is an interesting model proposed long time back [1] in order to create a bridge between the two most successful standard models in physics. In one hand we have the standard model of particle physics which has been experimentally verified to an extremely great precision. On the other hand, standard model of cosmology reached to a level where the robustness is just an undeniable fact. However, both models have one striking similarity at their respective high energy scale of interest at which extensive research are still going on. In particle physics, the Higgs mechanism is an integral part, which is controlled by a scalar field called Higgs, which has been recently discovered [2, 3]. However, properties of this field is not very well understood yet. Similarly, in the cosmology, the inflationary mechanism [4–6] is also believed to be an integral part, which can be best explained by incorporating a scalar field called inflaton. However, the way, we have understood the Higgs because of its experimental accessibility, is unlikely for the inflaton case. Because of the huge energy gap between the TeV scale Higgs physics and usually nearly GUT scale inflaton physics, it is hard to believe the existence of any connection between the two. Any endeavour towards making this identification would be very challenging from the effective field theory point of view. The main challenge to realise the minimal Higgs inflation without any further modification, is the lack of tuning parameter. All the parameter associated with the Higgs field are fixed by the TeV scale physics such as dimensionless Higgs quartic coupling, λh^4 , is constrained as $0.11 < \lambda < 0.27$ [7]. On the other hand, it has been shown that one requires $\lambda \leq 10^{-9}$ to produce right magnitude of density fluctuation during inflation. Therefore, to circumvent this problem, the very first attempt towards this direction was made by [1], and subsequently various other roots

have been taken [8–10] to identify Higgs as an inflaton field. The main ingredient of all those inflation scenarios is a non-minimal Higgs-gravity coupling. However, immediately after the proposal, all those models have been questioned considering unitarity issue [11–13].

In this letter we propose a new Higgs inflation scenario, where instead of introducing non-minimal coupling with the gravity we rather modify the potential at the ultra-violet regime in such a way that the TeV scale contribution of those modifications could be suppressed by a new scale α . However, full quantum field theory analysis is required to verify this. Through naive dimensional analysis of operators, we consider the following two possible form of the Higgs quartic potentials,

$$V_h = \begin{cases} \frac{\lambda}{4} \frac{(\mathbf{H}^\dagger \mathbf{H} - v^2)^2}{1 + \frac{(\mathbf{H}^\dagger \mathbf{H})^2}{\alpha^4}} \\ \frac{\lambda}{4} \frac{(\mathbf{H}^\dagger \mathbf{H} - v^2)^2}{\left(1 + \frac{(\mathbf{H}^\dagger \mathbf{H})}{\alpha^2}\right)^2} \end{cases} \quad (1)$$

Where, \mathbf{H} is the SU(2) Higgs doublet. From the experiment we know $\lambda \simeq 0.11 - 0.24$ and Higgs vacuum expectation value $v = 246$ GeV [7]. For the each potential form, the value of new scale α will set the scale of inflation. Therefore, both the potentials will contribute an infinite series of α suppressed operators at the perturbative label at TeV scale. From the low energy quantum field theory point of view, naive power counting analysis also suggests that the unitarity may be violated at scale α . However, it may not be a problem for our proposal, since the inflationary dynamics includes infinite series of higher dimensional operators. In addition another important fact is that the background dependent cut unitarity scale $\Lambda(h)$ turned out to be much larger than the above tree level unitarity scale i.e. $\Lambda(h) \gg \alpha$. Detailed analysis of this issue should be done before we get to any conclusion. Studying the phenomenological aspects of those operators could also be important at TeV scale. Nevertheless, the basic requirement of any Higgs inflation scenario is to reproduce all cosmological quantities con-

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sidering the parameters (λ, v) at their TeV scale value. Hence, our goal is to pin down the value of the new scale $\alpha (\gg v)$ in consistent with the cosmological observation made by PLANCK [14]. Since, we are interested in inflation, we can take the real component of the Higgs field h , so that the inflationary potential will turn out to be

$$V_h = \begin{cases} \frac{\lambda}{4} \frac{h^4}{1+h^4} \\ \frac{\lambda}{4} \frac{h^4}{\left(1+\frac{h^2}{\alpha^2}\right)^2} \end{cases} \quad (2)$$

Therefore, we start with the following Einstein-Hilbert action with the minimally coupled Higgs field, action,

$$\mathcal{S}_H = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_p^2 R - \frac{1}{2} \partial_\mu h \partial^\mu h - V_h \right], \quad (3)$$

where $M_p = 1/\sqrt{8\pi G} = 2.45 \times 10^{18}$ GeV, is the reduced Planck mass. R is the Ricci scalar. Considering the usual FRW metric,

$$ds^2 = -dt^2 + a^2(t)(dx^2 + dy^2 + dz^2), \quad (4)$$

the equations of motion for the metric and the Higgs field h are:

$$3M_p^2 H^2 = \left(\frac{1}{2} \dot{h}^2 + V_h \right), \quad \ddot{h} + 3H\dot{h} + V_h' = 0. \quad (5)$$

In order to achieve sufficient number of efolding, we identify various "slow-roll" parameters as follows,

$$\epsilon = \frac{M_p^2}{2} \left(\frac{V_h'}{V_h} \right)^2; \quad \eta = M_p^2 \frac{V_h''}{V_h}; \quad \xi = M_p^4 \frac{V_h' V_h'''}{V_h^2} \quad (6)$$

During the inflation, all those parameters has to be much smaller than unity. Therefore, violation of smallness of any one of those slow roll parameters will end the inflationary dynamics. Usually we take $\epsilon \simeq 1$ to identify the end of inflation. To set the beginning of inflation, we define another important cosmological quantity called efolding number, which measures the amount of inflation required to explain our observed universe. The expressions for the efolding numbers are,

$$N = \begin{cases} \frac{\alpha^2}{4M_p^2} \left(\frac{(\tilde{h}^6 - \tilde{h}_{end}^6)}{6} + \frac{(\tilde{h}^2 - \tilde{h}_{end}^2)}{2} \right) \simeq \frac{\alpha^2}{24M_p^2} \tilde{h}^6 \\ \frac{\alpha^2}{4M_p^2} \left(\frac{(\tilde{h}^4 - \tilde{h}_{end}^4)}{4} + \frac{(\tilde{h}^2 - \tilde{h}_{end}^2)}{2} \right) \simeq \frac{\alpha^2}{16M_p^2} \tilde{h}^4. \end{cases} \quad (7)$$

Where, we have defined dimensionless field $\tilde{h} = h/\alpha$, and the suffix "end" corresponds to the value of Higgs field at the end of inflation, specifically at the point where the slow roll parameter $\epsilon \simeq 1$. Therefore, depending upon the requirement of the number of efolding, we get the initial value of the inflaton. In this letter we will consider $N = (50, 60)$, and their predictions for the inflationary observables (n_s, r) . The scalar spectral index n_s and the tensor to scalar ratio r are related to the slow

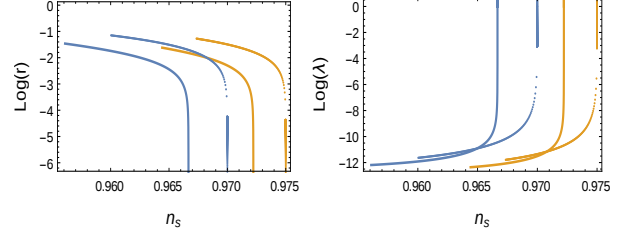


FIG. 1: In the left we plotted $(n_s \text{ vs } \log \lambda)$, and in the right we plotted $(n_s \text{ vs } \log r)$. We have considered $N = (50, 60)$. For all the plots, blue curves are for $N = 50$, and orange curves are for $N = 60$. The solid curves are for the first model and the dotted curves are for the second model. Every point on a particular curve corresponds to a particular value of inflationary energy scale α . We considered α within the range $(0.0001, 100)$ in Planck unit. As one decreases the value of α each models has stabilized values of n_s . However, the value of (r, λ) become sensitive at lower value of α .

roll parameters we have defined earlier eq.(6) as follows:

$$1 - n_s = 6\epsilon - 2\eta \simeq \begin{cases} \frac{5}{3} \frac{N}{2N} \\ \frac{4}{3} \left(\frac{\alpha}{M_p} \right)^{\frac{4}{3}} \frac{1}{N^{\frac{3}{2}}} \end{cases} \quad (8)$$

For the above final expressions, we have used the condition $\alpha < M_p$, and also ignored the contribution from the h_{end} in eq.(7). In the expression for spectral index, one sees that the leading order contribution is coming from slow roll parameter η , whose leading behaviour does not depend on α . We also numerically checked our claim. Important to notice that the predictions of r for both form of the potentials turned out to be very small ($\ll 0.11$) in consistent with the PLANCK result. We also see this fact in the left panel of Fig.(1), specifically the vertical part of the curves. Associated with the efolding number (N), and the tensor to scalar ratio (r), a quantity of theoretical interest called Lyth bound [15], Δh , is defined. This quantity tells us the maximum possible value that the inflaton can travel during inflation. From the effective field theory point view, the Lyth bound can question the effective validity of a particular model under consideration at an energy scale of interest. The bound on this field excursion Δh can be expressed as,

$$\Delta h \gtrsim N M_p \sqrt{r} = \begin{cases} \frac{M_p}{3^{\frac{2}{3}}} \left(\frac{\alpha}{M_p} \right)^{\frac{2}{3}} N^{\frac{1}{6}} \\ \frac{M_p}{\sqrt{2}} \left(\frac{\alpha}{M_p} \right)^{\frac{1}{2}} N^{\frac{1}{4}}. \end{cases} \quad (9)$$

As one can immediately see that Δh , contains the parameter α with a positive power. Therefore, we will see, our minimal model naturally gives sub-Planckian field excursion if we demand the Higgs quartic coupling to be of order unity. At this point we would like to point out that, our minimal Higgs model does not belong to the class of recently proposed supergravity inspired inflationary α attractor [16] models, as those models predict

$1 - n_s \simeq 2/N$, $r \simeq 12\alpha/N^2$, for $\alpha \leq \mathcal{O}(10)$ and large N . Interestingly, the usual Higgs inflation model [1] is one of the members in that class of models. Therefore, it would be interesting to find out supergravity origin of our models. Another interesting observable which also can constrain various inflationary models is the running of spectral index, which can be expressed as

$$dn_s^k = \frac{dn_s}{d \ln k} = -24\epsilon^2 + 16\epsilon\eta - 2\xi \simeq \left\{ \begin{array}{l} \frac{-5}{6N^2} \\ \frac{-3}{4N^2} \end{array} \right. \quad (10)$$

In the above expression, we only keep the leading order in N . Important to see that, it does not depend upon the value of α . Therefore, we will have definite but small prediction for the running of scalar spectral index. To the leading order in N , the behaviour of spectral running is same as the usual chaotic inflation. We also have numerically checked the validity of all the approximations made in the above expressions. So far all the quantities we discussed are independent of λ . The constraint on λ can be obtained from the [17], the primordial power spectrum of the curvature perturbation:

$$\mathcal{P}_\zeta = \left\{ \begin{array}{l} \frac{\lambda \alpha^6 \tilde{h}^6 (1 + \tilde{h}^4)}{12 \times 64 \pi^2 M_p^6} \simeq \frac{\lambda}{4\pi^2} \left(\frac{\alpha}{M_p} \right)^{\frac{8}{3}} N^{\frac{5}{3}} \\ \frac{\lambda \alpha^6 \tilde{h}^6}{12 \times 64 \pi^2 M_p^6} \simeq \frac{\lambda}{12\pi^2} \left(\frac{\alpha}{M_p} \right)^3 N^{\frac{3}{2}} \end{array} \right., \quad (11)$$

where, ζ is the variable for gauge invariant scalar perturbation, Through out our analysis, we will be considering PLANCK central value of $n_s = 0.9682 \pm 0.0062$ and the normalization for $\mathcal{P}_\zeta = 2.4 \times 10^{-9}$ at the pivot scale $k = 0.005 Mpc^{-1}$. For the minimal Higgs like quartic potential, field value takes $h \geq M_p$, in order to achieve sufficient number of e-folding, and correct amplitude of density perturbation leads to an unnatural value of the Higgs quartic coupling i.e $\lambda \leq 10^{-9}$. This is believed to be an unnatural value for a dimensionless number, which means radiatively unstable from the quantum field theory point of view. More importantly, it leads to a huge mismatch with the standard model prediction, $0.11 < \lambda \lesssim 0.27$ [7]. As mentioned before, to circumvent this problem, the first model was proposed in [1] by introducing a non-minimal coupling of the Higgs with the Ricci scalar such as $\mathcal{L}_{int} \sim \xi h^2 R$, where ξ is the dimensionless coupling. The value of $\xi (\geq 44700\sqrt{\lambda})$ is very high to maintain the flatness of the potential during inflation. However, the model has been questioned, as unitarity [11, 12] may violate much before the inflationary energy scale. However, subsequently in the reference [18], the author introduced the concept of background field dependent cut off, so that the unitarity scale could be very high compared to the previous claim. In another model, a more complicated, Einstein tensor $G^{\mu\nu}$ coupled with the kinetic term of the Higgs field, $G^{\mu\nu} \partial_\mu h \partial_\nu h$ [8, 9] has been considered, but claimed to be plagued with the unitarity problem [13] ignoring the background effect. However, again background effect can solve this issue as shown in [19]. In another attempt, a non-trivial galileon

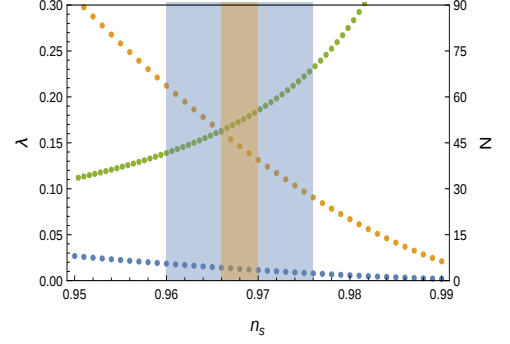


FIG. 2: On the same figure, we have plotted $(n_s \text{ vs } \lambda)$ and $(n_s \text{ vs } N)$, for two different values of $\alpha = 0.001, 0.0004$ in Planck unit. a) $(n_s \text{ vs } \lambda)$ plot: The (blue, orange) dotted curves are for $\alpha/M_p = 0.001, 0.0004$ respectively. b) $(n_s \text{ vs } N)$ plot: The green dotted curve is for both α values, as both turned out to be superimposed. This plot is for the first model. The behaviour will be same for second model with the value of α , which is one order of magnitude less compared to value we considered for the first model. We also showed the bounds on n_s from PLANCK. 1σ bounds on n_s , corresponds to the light blue shaded vertical region. 1σ bounds of a further CMB experiment with sensitivity $\pm 10^{-3}$ [22, 23], corresponds to brown shaded region. For all those bounds, the central value $n_s = 0.9682$ is considered.

[20] type modification of higgs field has been studied, specifically by adding higher derivative operator such as $F(h)\partial_\mu h \partial^\mu h$ [10], in addition to the usual terms. Similar background dependent cut off analysis has been done in [21]. All the aforementioned models are significantly constrained mainly because of nonrenormalizable interactions, that have been introduced to get the slow roll condition. This provides tight constraints on the model parameters. In our model we have introduced only perturbative interaction terms at the level of TeV energy scale. Before we go further on the theoretical description, let us provide our model predictions to the leading order in N , for all the cosmologically as well as theoretically relevant quantities. As we mentioned before, considering the e-folding number to be $N = (50, 60)$, we found

$$\begin{aligned} \frac{\alpha}{M_p} &\simeq \left\{ \begin{array}{l} (0.0004, 0.0003) \\ (0.0015, 0.0014) \end{array} \right\} ; n_s \simeq \left\{ \begin{array}{l} (0.967, 0.972) \\ (0.970, 0.975) \end{array} \right\} \\ \frac{\Delta h}{M_p} &\simeq \left\{ \begin{array}{l} (0.017, 0.016) \\ (0.21, 0.21) \end{array} \right\} ; r \simeq \left\{ \begin{array}{l} (2 \times 10^{-8}, 1 \times 10^{-8}) \\ (9 \times 10^{-6}, 6 \times 10^{-6}) \end{array} \right\} \\ \frac{dn_s}{d \ln k} &\simeq \left\{ \begin{array}{l} (-0.0003, -0.0002) \\ (-0.0003, -0.0002) \end{array} \right\} \end{aligned} \quad (12)$$

For the above predictions of our model, we assume a sample value for the Higgs quartic coupling $\lambda = 0.2$, which is same as its TeV scale value. If we consider the PLANCK central value of the scalar spectral index, $n_s = 0.968$, with the same λ value, our model predicts the number of e-folding $N \simeq (52, 47)$ for first and the second form of the potential respectively. All the other aforementioned quantities remain almost the same in terms of order of magnitude. However, it is important to point out that because of renormalization group (RG) running, the value of Higgs quartic coupling decreases from its TeV scale value as one increases the

energy. Keeping this in mind in Fig(2), for the first form of the potential, we consider two different values of $\alpha = 0.001, 0.0004$ in unit of M_p , and show how (λ, N) value changes with n_s . According to the present standard model calculation, it is shown that Higgs quartic coupling may hit the zero value and turn into negative at the scale within, $10^9 - 10^{14}$ GeV, depending upon different values of Higgs mass, 125 GeV $m_h < 126$ GeV, top mass, $m_t = (173.2 \pm 0.9)$ GeV [24], and the electromagnetic coupling $\alpha_s = 0.1184 \pm 0.0007$ GeV [25]. However, we will not discuss about this stability bound in the current context. Of course we would like to point out that in our proposal, the original Higgs potential contains an infinite series of $\alpha \simeq (10^{-4}, 10^{-3}) M_p$ suppressed operator for the first and second forms of the Higgs potential respectively, at TeV scale. Therefore, modification to all the aforementioned bounds need to be calculated, and those will be extremely important on the stability bound. Form the cosmological point of view, we see our model perfectly fits with the cosmological observation, see Fig.2, within $N \simeq 45 - 65$ efolding number. Prediction of tensor mode is almost negligible within a huge range of α , making it very difficult to be observed in the foreseeable future. We also point out that our minimal model predicts sub-Planckian field excursion, $\mathcal{O}(10^{-2}M_p)$, within the required value of λ . It is worth mentioning that the current PLANCK bound on running is given as $dn_s^k = -0.003 \pm 0.007$ combined with the Planck lensing likelihood. Hence our predicted value is outside the PLANCK sensitivity.

Inflationary energy scale and Reheating Temperature: As we have seen, in order to have an excellent agreement with the current observation by PLANCK on the inflationary observables, our minimal Higgs inflation requires a scale $\alpha \simeq 10^{14}$ GeV for the first model, and $\alpha \simeq 10^{15}$ GeV for the second form the potential, such that TeV scale quartic Higgs coupling remains of the order of unity. Related to this prediction of α , another important quantity of interest is inflationary energy scale which we defined as $\mu \simeq V_h^{1/4} \simeq (\lambda/4)^{1/4} \alpha \simeq (10^{14}, 10^{15})$ GeV for both the models. It is important to notice that, our predicted inflationary energy scale is almost at the higher edge of the Higgs vacuum instability bound mentioned before. This also means that Higgs mass $m_h \simeq 126$ GeV could be favourable. Another interesting fact is that the inflationary Hubble scale turned out to be significantly lower than the energy scale α

$$H \simeq \lambda^{\frac{1}{2}} \left(\frac{\alpha}{M_P} \right)^2 M_P \simeq (10^{11}, 10^{12}) \text{ GeV}. \quad (13)$$

This is much lower than the naive cut off scale α mentioned before. However, as we mentioned, unitarity has to be re-analysed in order to make any such concrete conclusion.

Even though the inflationary energy scale sets the higher limit of the total energy budget of the universe,

important quantity is the amount of energy transferred from the inflaton to matter field, which is very important for the subsequent evolution of the universe. An important part of any inflationary cosmology is the mechanism of energy transformation which we call reheating phase of the universe. This is the phase when most of the inflaton energy density is transferred to the usual matter fields which we observe today. This is phase which is not very clearly understood. We will not be doing detail computation at this stage. However, an approximate estimate can be done on the upper bound of the most important quantity called reheating temperature, T_{re} , based on the assumption that the reheating, and the subsequent thermalization happens after the inflation because of the interactions of the Higgs boson with the standard model particles. The maximum possible transferred matter energy density (ρ_m) after the reheating phase can be identified with the inflaton energy density ($\rho_{h_{end}}$), when $\epsilon(h_{end}) \simeq 1$, is satisfied. This is the condition for the end of inflation, we have considered before. Hence, one can arrive at following equality

$$\rho_m \simeq \rho_{h_{end}} \simeq 2V_{h_{end}}. \quad (14)$$

Energy transfer and thermalization of the matter field generally are not the instantaneous process. Therefore, equilibrium temperature which mentioned before as a reheating temperature, T_{re} , of the produced relativistic matter field will be in general smaller than the maximum value attainable. In thermal equilibrium the energy density of a relativistic matter field can be expressed in terms of equilibrium temperature as,

$$\rho_m = \frac{g_* \pi^2 T_{re}^4}{30}, \implies T_{re} \lesssim \begin{cases} 10^{13} \text{ GeV} \\ 10^{14} \text{ GeV}, \end{cases}$$

where $g_* \simeq 106.75$ is the numbers of relativistic degree of freedom during reheating. Therefore, maximum reheating temperature will well below the Planck scale. This is consistent with the constraint from Big Bang Nucleosynthesis.

Background dependent unitarity: As mentioned before standard power counting analysis tells us that the tree level unitarity scale Λ_{tree} should be of the order of same as inflationary energy scale α . It is already well established that in standard model unitarity is dependent upon the Higgs vacuum expectation value. Therefore, this should also be true in the present context. From general power counting argument, the background dependent cut off scale $\Lambda(h)$ can be read off from the coefficient of the operator of dimension higher than four. In our minimal Higgs inflation scenario, all the higher dimensional operators come from the expansion of V_h in the inflationary background h_0 by expanding $h = h_0 + \delta h$. After expansion, the five dimensional operator turned out to be

$$\delta V_h = \begin{cases} \frac{8\lambda \tilde{h}_0^3 (-7 + 57\tilde{h}_0^4 - 57\tilde{h}_0^8 + 7\tilde{h}_0^{12})}{\alpha(1 + \tilde{h}_0^4)^6} \delta h^5 \\ \frac{12\lambda \tilde{h}_0 (-1 + 7\tilde{h}_0^2 - 7\tilde{h}_0^4 + \tilde{h}_0^6)}{\alpha(1 + \tilde{h}_0^2)^7} \delta h^5 \end{cases} \quad (15)$$

Therefore, at large field limit $\tilde{h} \gg 1$ (inflationary regime), one finds

$$\delta V_h = \frac{1}{\Lambda(h)} \delta h^5 \implies \Lambda(h) \simeq \begin{cases} \frac{\alpha}{56\lambda} \tilde{h}^9 \\ \frac{\alpha}{12\lambda} \tilde{h}^7 \end{cases}$$

This is much larger than the tree level unitarity limit α . Therefore, our inflationary predictions could be robust against quantum corrections. We defer the detailed unitarity analysis for future study. However, interesting point to mention, some odd behaviors are turning up for $0.4 < \tilde{h} < 2.5$ because of the presence of zeros of $\Lambda(h)$ for some specific values of \tilde{h} . It could be interesting to understand this peculiar behavior.

Discussions and Conclusion. In this Letter we have proposed a new Higgs inflation scenario, where, the field is minimally coupled with gravity. In the usual Higgs inflation, a non-minimal coupling of the Higgs field with the gravity is introduced. The non-minimal coupling keeps the Higgs potential sufficiently flat by increasing the effective Higgs field dependent gravitational coupling. In our minimal Higgs inflation scenario, we modified the potential by introducing a new scale α in such a way that it creates a large flat plateau for the potential at the inflationary energy scale $\mu \sim \lambda^{1/4} \alpha$. Therefore, our modified Higgs potential naturally contributes an infinite series of higher dimensional operators at the TeV scale, however, we expect the contribution of those operators on the usual standard model observables to be significantly suppressed by the aforementioned inflationary energy scale μ . It is therefore, important to check how, the coupling constants of those infinite series of higher dimensional operators flow towards the TeV scale under RG flow. By now we understood the fact that all the non-minimal Higgs inflationary models are plagued by unitarity issue, or is tightly constrained. Therefore, alternative scenarios are welcome in this regard. As we have explained through out this paper, our minimal Higgs model fits extremely well with all the observations made by PLANCK related to the inflationary dynamics. More specifically, for both form of the Higgs potential, prediction of tensor to scalar ratio turned out to be very small ($r < 10^{-5}$), which is very difficult to observe in near future. It is also worth pointing out that because of the minimal single field inflationary scenario, the non-gaussianity will also be very small [26]. For both the form of the potentials the value of scalar spectral index turned out to be $n_s = (0.967, 0.972)$ considering $N = 50$. We also computed the background field dependent unitarity scale $\Lambda(h)$, which turned out to be much larger than the tree level unitarity scale α . Currently we are working on more detail analysis of our models from the cosmology and the particle physics point of view.

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